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DEVELOPMENT OF A METHODOLOGY FOR DESIGN OF OPTIMUM-ILLUMINATION FLARE SYSTEMS

Final rept.

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A methodology for the design of more effective flare systems, using a realistic computer simulation model, has emerged from a comprehensive experimental and systems analysis program. The program involved: designing and building a detailed scaled terrain model and illumination source to conduct well-controlled experiments on flare performance; determining standards for and experiments to test flare performance; experiments to determine the dependence on illumination required for given recognition probabilities on relevant factors

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(such as flare-target-observer angles and nature of background); computer programming and preliminary testing of the model, and developing a strategy for making decisions based on the model's computer results and user-specified requirements.

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INTRODUCTION

Military pyrotechnic illuminating systems, whether launched by aircraft, artillery, mortar, or rocket, contain a flare pellet which is ignited simultaneously with the ejection of a parachute system deployed to slow the descent. Present flare pellets produce nominally constant intensity. The illumination on the ground below the flare continually increases as the flare descends.

Substantial improvements in performance and cost effectiveness would result from design optimization. However, field-testing of designs has proven costly, produced few results, and generally has not included all relevant parameters. Also, attempts to optimize flare design by means of a mathematical model have been limited by unrealistic assumptions about recognition probabilities, an inability to handle complicating features (such as wind) and inadequate tailoring of the performance to user requirements (ref. 3).

The present paper describes a methodology for assessing flare performance and design, a mathematical model to implement it, and a computer program to handle the calculations (we term this combination the MODEL). This is the culmination of a broad research effort involving the design and construction of a pyrotechnic terrain model (a scaled model of a typical landscape) together with an illumination system, experiments, and analysis. The MODEL and preliminary results are emphasized, and the supporting work only briefly summarized.

BACKGROUND

Studies have been conducted at Picatinny Arsenal utilizing the pyrotechnic terrain model (ref. 4) to determine the flare illumination levels required to recognize targets. These studies have shown that the illumination levels provided by most standard flares are far from adequate to satisfy typical military requirements.

Decisions on three major areas of trade-off must be made in flare system design:

1. Flare intensity vs burning time. If candlepower is increased then burning time is correspondingly decreased for the same size pellet. As a rough "rule of thumb", the candlepower can be considered inversely proportional to the burning time.

2. Pellet size vs parachute size. Increasing the parachute size results in a lower average descent velocity for a given (fixed volume) round, so ignition can occur at a lower altitude. While this yields more illumination of the target for a given candlepower, it entails a decrease in pellet size and, hence, in the total integrated intensity.

3. Factors relating to the controlled positioning of flares (such as allowable variations in fuze accuracy, burning time of pellet, and descent rate) vs cost.

Recent studies (ref. 5) emphasized the importance of these parameters in obtaining the most effective illuminating flare systems. For example, variations in the design parameters of existing flare systems can lead to a three-fold increase in initial illumination on the ground, and this illumination can be maintained for the same total burning time. Small changes in burning time can significantly affect the illumination level on the ground. A reduction of 30% in burning time can result in a seven-fold increase in initial illumination.

APPROACH

The majority of military purposes for illumination rounds fall into one or more of the following operational modes:

1. The fixed target mode. Typically, to illuminate a particular target in an approximate position in order to direct lethal fire effectively, or to assess damage.

2. The fixed area mode. Typically, to illuminate a peripheral area of a defensive position in order to minimize the possibility of infiltration.

3. The search mode. To search out enemy positions and targets over very large areas.

Since different effectiveness criteria are required for each of these modes, "optimum design" is not unique. In addition, different environmental conditions (wind velocity and direction, type of terrain, and atmospheric condition) and tactical situations (range of observer from target area, type of target, and area of interest) are expected to lead to different "optimum designs."

Since practicality precludes matching a different flare system to each conceivable situation, some compromises are necessary. Our approach is to optimize (by computer) effectiveness values for all three modes and for a variety of environmental and tactical situations. These can be assessed on the basis of a feedback interaction with user agencies to determine the best design.

Each computer run optimizes deployment (height and horizontal displacement relative to observer and target), and produces optimum deployment tables.

DEPENDENCES AND PARAMETERS IN THE MODEL

Intensity, Geometry Dependences, and Contrast

Experiments conducted on the pyrotechnic terrain model comparing flare performance under high and low contrast background conditions have shown that the illumination required for 90% recognition is significantly different in each case. Low contrast data is presently incorporated in the MODEL for the following reasons: high contrast data is less extensive to date, the likelihood of enemy targets choosing a high contrast background (such as a black tank in a desert environment) is considered small, and flare systems optimized for low contrast situations would perform even better under high contrast conditions.

The dependences of recognition probability on flare illumination, observer-target distance, and flare-target-observer angle were deduced from experiments using the pyrotechnic terrain model. The data and methodology of its collection are available in a previous publication (ref. 4). The analytical dependences chosen for present purposes are briefly described below. It is assumed that the dependences are completely separable.

To isolate the illumination dependence from other factors, a critical illumination level (E_c) resulting in recognition with a probability of about 85%, is defined. E_c may vary strongly with changes in relative distances and angles, nature of the background, etc. As described in an earlier report (ref. 6), a plot of recognition probability, P_r vs E/E_c (where E is the actual illumination present), spanning various physical conditions, leads to a reasonably smooth curve. Figure 1 represents the data with our choice of analytical fit:

$$P_r = 1 - \frac{1}{5(E/E_c)^2 + 1} \qquad (1)$$

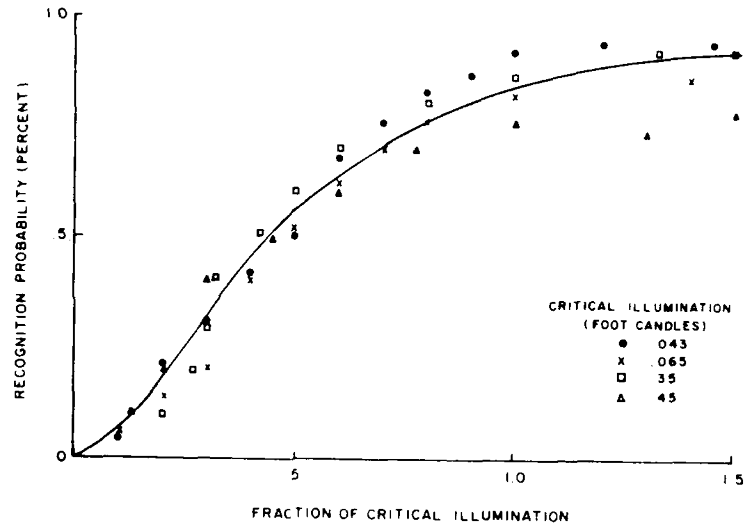

Figure 1. Recognition probability function (P_r) compared with experimental values obtained for four different conditions of critical illumination (E_c).

This choice has the advantages of reasonable fit to the data and efficiency of computation for computer purposes.

E_c is assumed to be proportional to the square of the observer-target distance. While there is no convincing fundamental argument underlying the choice, it is in gross agreement with available experimental data.

The dependence of E_c on flare-target-observer relative angles follows from data collected using the pyrotechnic terrain model. A detailed analysis of the data will appear elsewhere, along with a theory that yields a good analytic fit to the data.[1] The important feature is that E_c can be expressed as a function of the single angle $\beta = 180° - \alpha$, where α is the angle between the lines connecting the observer to the target and the flare to the target. With other parameters (background contrast, range, etc.) held constant, it follows that

$$E_c = (\text{constant}) \times \left(\frac{1 - 0.75 \cos \beta}{1 + 0.75 \cos \beta}\right) \qquad (2)$$

This function is plotted in figure 2. Note that recognition for larger values of β (smaller values of α) requires substantially greater illumination than for small to intermediate values of β.

Parachute Volume and Descent Rate

The design of a particular pyrotechnic system is limited to a specific total volume (V_t) which includes the packed parachute (V_c), pellet (V_p), and fuze (V_f) volumes, such that

$$V_t = V_c + V_p + V_f. \qquad (3)$$

The fuze volume is generally small compared to the others, and, as it is essentially independent of fuze quality (accuracy), it is neglected in this analysis.

The relationship used to express the descent velocity (u) as a function of the mass of the payload (which varies with time as the pellet

[1] T. Gora and P. Kemmey, unpublished work.

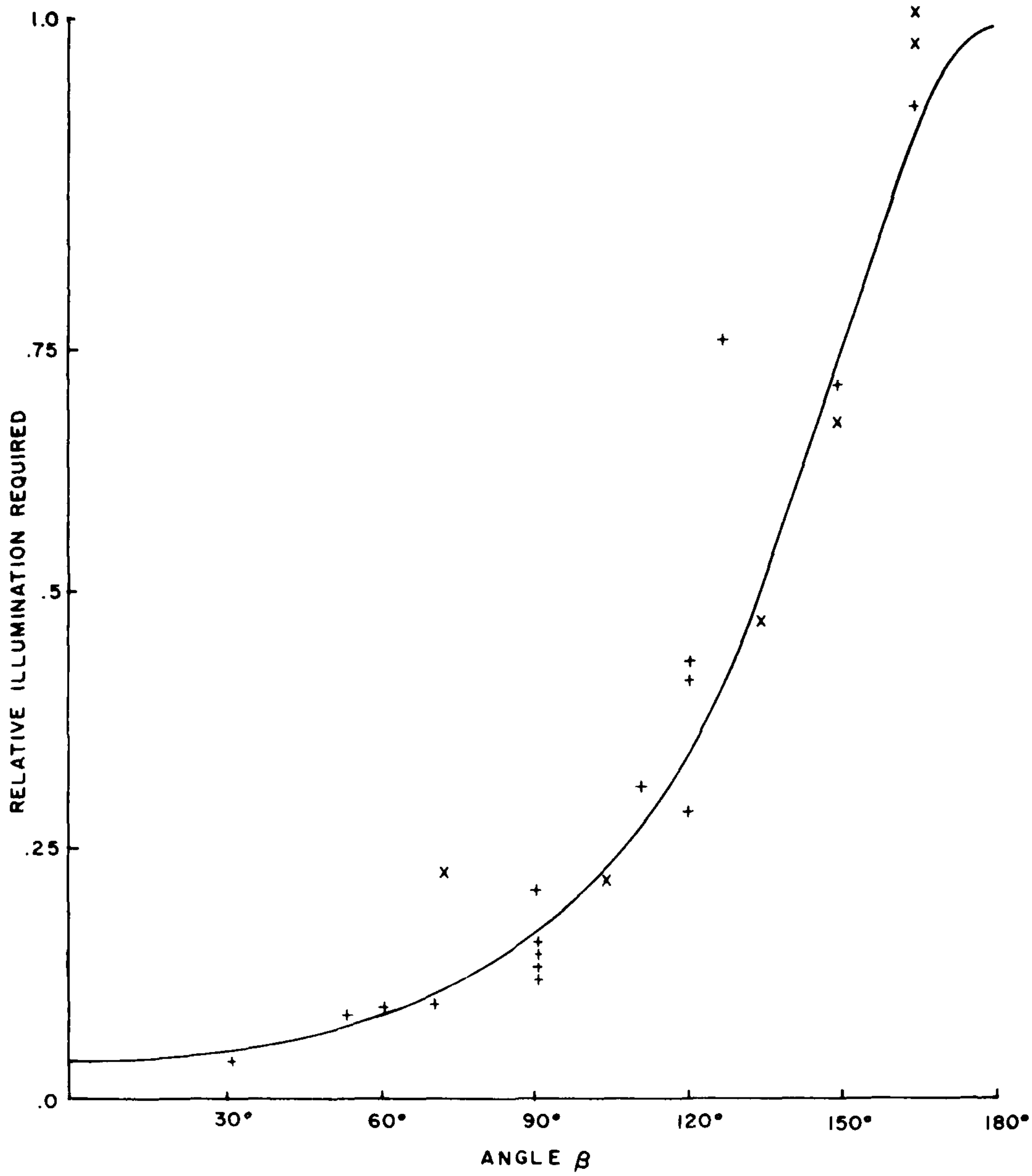

Figure 2. Critical illumination function (E_c) compared with experimental values.

is consumed) is

$$u^2 = K_1 \frac{(m_o - \int_o^T B_r dt)}{m_p} , \qquad (4)$$

where: K_1 (constant) depends on the packing factor, drag coefficient, etc.;

m_o is the initial value of the suspended mass attached to the parachute;

and m_p is the mass of the parachute.

Burning Rate and Intensity

Intensity (I) is approximately proportional to the burning rate (B_r) (composition mass consumed per unit time),

$$I = K_2 B_r, \qquad (5)$$

where the dependence of the proportionality constant (K_2) on case material and flare diameter can be determined experimentally.

Wind Input

A literature search (ref. 7) was conducted to determine an approximate wind velocity distribution function averaged over geographical and seasonal variations. The wind distribution presently incorporated in the MODEL is plotted in figure 3. Observer-target direction is considered to be completely random, so that the wind direction (which may have a favored direction at a given location) relative to it may be taken to be random, also. Thus, the MODEL assigns equal weights to all relative directions. It is assumed that wind velocity and direction are constant throughout a flare's burn.

Search Simulations

The search mode is used when the observer is asked to detect and recognize targets anywhere in his field of view. The literature (refs. 8 & 9) on visual search techniques in a number of applications suggests the following: After a brief orientation period, the observer chooses a particular potential target point and fixates on it for a discrete time interval (the dwell time) to make a decision; if a target is not recognized at the first point, his attention rapidly transfers to another fixation point; the procedure is iterated until target recognition is achieved or all fixation points

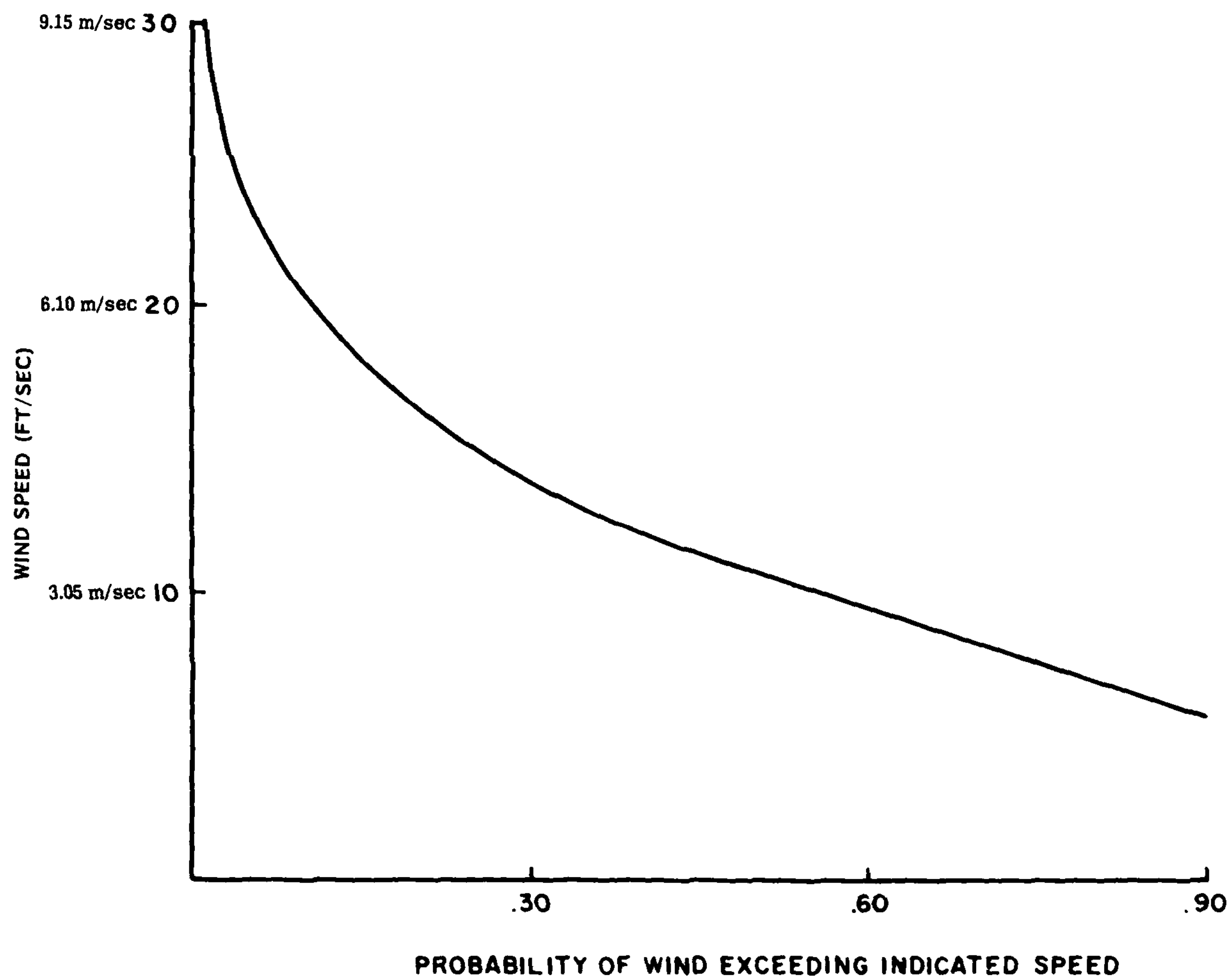

Figure 3. "Typical" wind distribution used in model, with a mean speed of 3.2 miles/hour (13.2 km/hr).

are studied. This pattern appears to result from the limited resolving power of the eye for all but one or two degrees of field of view.

Our experiments[2] tend to confirm the validity of the search patterns, and yield dwell times of .25 to .70 seconds (depending on illumination level and complexity of the fixation points), as well as reasonable values for fixation point density. Literature values for dwell time fall within a 0.3 to 0.4 second range (ref. 10). Our model assumes a uniform density of fixation points, that each is visited but once, and that the order of visitation is determined by brightest illumination. There is experimental support in the literature (ref. 11) for the latter assumption.

User Requirement Parameters, Parameter Flexibility

The anticipated applications of our MODEL involve a feedback process: The user would make some preliminary decisions on the essentials in a flare system, the MODEL would examine flare performance based on this information, and the user would receive trade-off dependences in order to make more detailed requirement decisions. For example, a flare design which is optimum at a particular range, but whose comparative effectiveness drops off sharply for other ranges, might be considered inferior to one whose effectiveness (while lower at that range) has a flat range dependence and gives better performance for a majority of combat situations.

The potentially most important user input requirements are: observer range and target type, approximate area to be illuminated, observer position (ground vs aerial), and frequency of use anticipated in each of the three operational modes described previously.

The MODEL is designed so the input representation of each parameter and mechanism could be altered or replaced as more accurate representations become available. Only observer recognition data is utilized for describing parameters involving recognition. A deliberate attempt is made to avoid inputs which involve physiological assumptions, such as extending Blackwell's basic detection data to recognition modeling (ref. 12). The MODEL is envisioned as evolving toward an accurate and more faithful portrayal of reality. Prime attention, thus far, has been devoted to overall philosophy and strategy. It is expected that experiments in progress and others being designed would yield more accurate values for all inputs used in the MODEL.

[2] R. Davis, F. Schroyer and J. Tyroler (unpublished results).

FLARE EFFECTIVENESS MODEL

Flare effectiveness (ξ_1) in the fixed target mode is defined by the integral,

$$\xi_1 \ (p,d,w) = \int_{o}^{T(p,d)} P_r(p,d,w) \ \varphi[P_r(p,d,w)-c] \ dt, \qquad (6)$$

where the recognition probability (P_r), defined in equation (1), is a function of all the input parameters (p), deployment parameters (d), and wind parameters (w). The function (φ) is defined such taht $\varphi(\chi) = 1$ when $\chi \geq 0$, and $\varphi(\chi) = 0$ when $\chi < 0$. The cutoff probability (c) (chosen as insures that only probabilities P $>$ c are integrated over time, as the 0.9 in the calculations) insures that only probabilities $P_r > c$ are integrated over time, as the fixed target tactical situation requires. Finally, the integration ends at a time T (p,d) such that either the flare burns out or descends below a cutoff height (taken as 10 ft (3.05 m) in the calculations). The units of ζ_1 are effective seconds.

In the fixed area mode, flare effectiveness (ζ_2) is defined as

$$\xi_2 \ (p,d,w) = \int G(A) \ \xi_1 \ (p,d,w) \ dA, \qquad (7)$$

where the integral is taken over all of area (A). G(A) defines the area of interest and can be a step function (equal to one within the area of interest and zero outside it). Our calculations allow G(A) to weight area interest in a more gradual sense and uses the two-dimensional Gaussian function to do this (different half-widths were tested). The units of ξ_2 are given by effective ft^2-sec (m^2-sec).

The search mode effectiveness (ξ_3) is defined as

$$\xi_3 \ (p,d,w) = \sum_{f=f_1}^{F} P_r[f(p,d,w,\tau_d)], \qquad (8)$$

where P_r is defined as before for the particular fixation point (f). The latter depends on the parameters [p,d,w, and τ_d (the dwell time)] because of the prescription that it be chosen as the most strongly illuminated point not previously visited from a predetermined fixation point grid. (Uniform density grids have been used in the calculations.) The final point (F) visited is a particular point $f(p,d,w,\tau_d)$ which is also determined by $T(p,d)$, defined earlier. The units of ξ_i are effective fixation points visited.

Flare effectiveness averaged over wind ($\bar{\xi}_i$) (i = 1 to 3 for the three models) is determined using the wind weighting function ($W(w)$) defined in figure 3,

$$\bar{\xi}_i (p,d) = \int^{w} W(w)\ \xi_i\ (p,d,w)\ dw, \qquad (9)$$

where integration is performed over all wind speeds and directions.

An optimization routine then determines values of the design parameters (included in p) and of deployment parameters (d) which maximize $\bar{\xi}_i$. Separate values of $\bar{\xi}_i$ are determined for each mode and for different ranges. Range is measured from the observer to the target in the fixed target mode, to the weighted center of G(A) in the fixed area mode, and to the point chosen for initial deployment in the search mode. The observer is always positioned near ground level (at 20 ft elevation (6.10 m)) in the calculations reported.

TEST CASE RESULTS

The MODEL (including its supporting computer program and a methodology for using its results) constitutes the major result of our efforts to date. Its capabilities are tested by a design optimization study which applies to the payload volume of a 155 mm howitzer illuminating shell. The results, while useful by themselves, demonstrate the relation between design parameters and performance and also indicate the areas where feedback from user agencies are most essential to the flare designer.

Values for all input parameters used in the test case are listed in table 1, including those that are specific to the 155-mm howitzer illuminating shell. Two independent design parameters are optimized, burning rate and ratio of the pellet to available volume. Deployment parameters are simultaneously optimized. The pellet composition efficiency (total output available for illumination per unit mass) is fixed in this example, but can be made dependent on burning rate and pellet diameter if experimentally justified.

Optimum flare design was determined at each of several ranges, in each of the three operational modes. The corresponding design parameters are listed in table 2, along with burn time.

Table 1. Constants used in model

Total volume available	.111 ft^3 ($3.14x10^{-3}$ m^3)($3.14x10^3$ cm^3)
Composition efficiency	$18.16x10^6$ candle-sec/lb ($4.00x10^4$ candle-sec/gm)
Composition density	109.8 lb/ft^3
Fraction of composition weight to total weight	.62
Parachute drag coefficient	.77
Parachute packing fraction	$1.58x10^3$ ft^2/ft^3 ($5.18x10^3$ m^2/m^3)
Air density	.00216 slugs/ft^3 (.00111 gm/cm^3
Dwell time	.33 seconds
Fixation point density	1240 points/$mile^2$ (479 points/km^2)
Radius of fixed area	600 ft (183 m)
Observer height	20 ft (6.1 m)
Normalized illumination condition	Recognition probability, 90% Range, 1400 ft (427 m) Angle (α), 90° Illumination required, 0.3 ft-candle (.028 meter-candle)

Table 2. Optimized design parameters

OPERATIONAL MODE*	T	A	S	T	A	S	T	A	S
DESIGN RANGE (FEET) (METERS)		2000 (610)			4000 (1219)			8000 (2438)	
INTENSITY (10^6 CANDLEPOWER)	1.2	1.2	1.3	1.7	1.8	1.8	3.0	3.3	3.3
BURN TIME (SECONDS)	118	112	110	81	74	72	50	46	44
PELLET RATIO (V_P/V_T)	.61	.58	.63	.61	.61	.61	.67	.67	.67

*T = FIXED TARGET
A = FIXED AREA
S = SEARCH

The remaining tradeoff decision involves which of these optimized designs (one for each range and each operational mode) is most effective in the mix of conditions (range and mode) appropriate to battlefield usage. To facilitate this decision, the effectiveness of a flare optimized for a particular range is assessed at other ranges. This is done separately for the three operational modes. The results for the fixed target mode are depicted in figure 4. Corresponding results for all three modes are presented in table 3, where effectiveness is normalized to 1.0 for the 2000 ft (610 m) optimized design in each mode.

For comparison, the present 155 mm round has a burn time of about 120 sec and a design similar to those optimized by the MODEL for a 2000 ft (610 m) range. The effectiveness of that design can be seen (table 3) to degrade severely for longer ranges. Designs optimized for longer ranges (e.g., 4000 ft (1219 m)) are reasonably effective at shorter and even longer ranges. Such designs involve greatly reduced burn times and give credence to the increasing user and designer tendency to favor faster burning flares.

The results, with respect to the 155 mm howitzer illuminating flare design, are

1. Optimized design parameters are strongly dependent on range, but relatively insensitive to choice of operation mode. Thus the user's range requirements must be heavily weighed in the ultimate design decisions.

2. The order of relative performance of various flare designs changes markedly as a function of observer range (see figure 4 and table 3). This is significant for the interpretation of field test results, since the apparent ordering of effectiveness is dependent on the choice of ranges used in the tests.

3. It may not be necessary for user agency requirements to be very detailed to assist in the ultimate decisions. For example, the search mode results of table 3 show that the design optimized to 4000 ft (1219 m) is also quite effective at 2000 ft (610 m) and 8000 ft (2438 m) range, and in this sense the best. In both cases (2000 & 8000) effectiveness degrades less than 15% (from 1.0 to .90, and from .41 to .35, respectively) from designs optimized to those ranges. Thus, only rough weightings of operational mode frequency and required range distribution appear to be necessary.

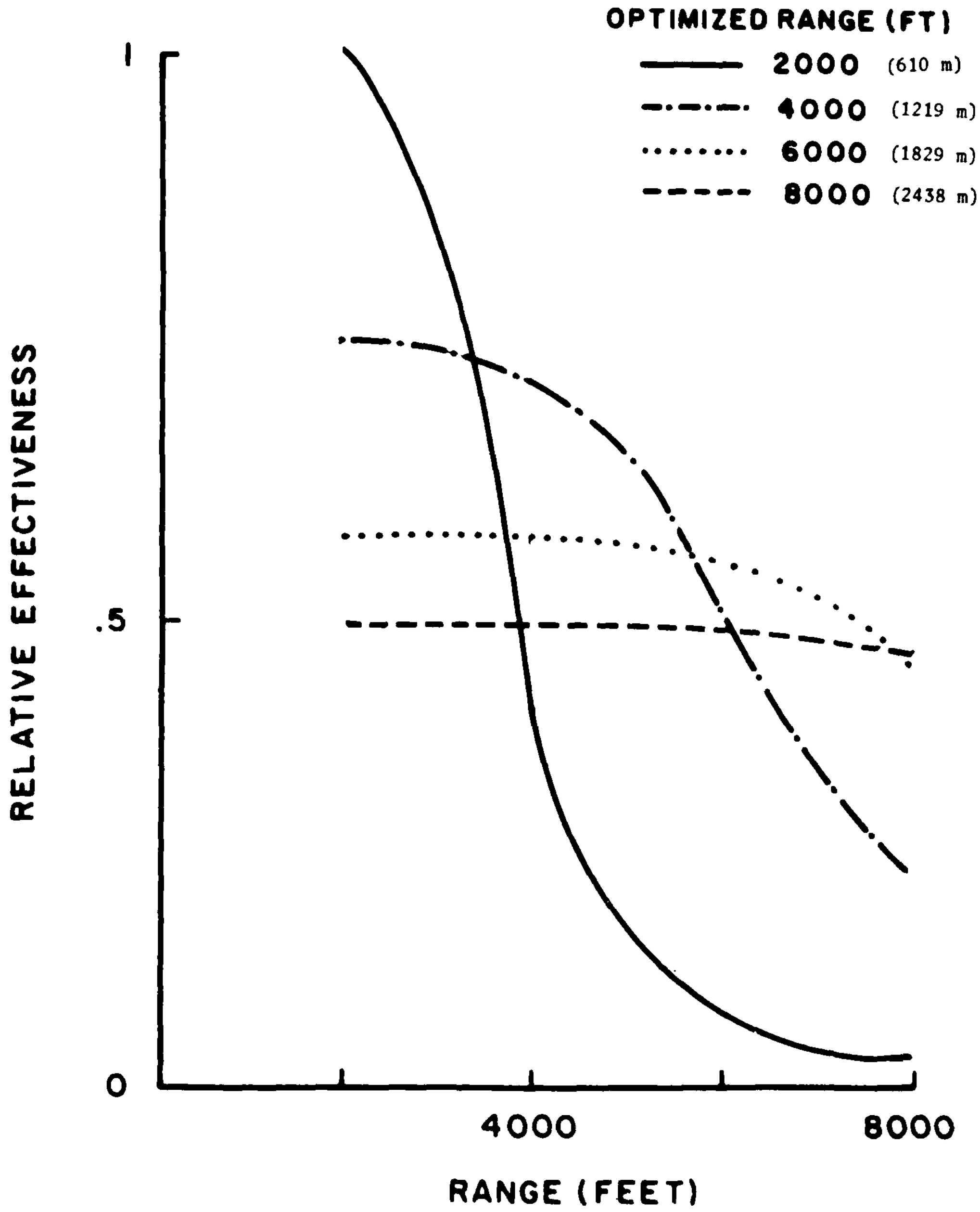

Figure 4. Comparative effectiveness of four flare systems as a function of range in the fixed target mode. Each system is optimized at the range indicated for maximum effectiveness.

Table 3. Effect of range on optimum flare design

OPERATIONAL MODE	FIXED TARGET			FIXED AREA			SEARCH		
DESIGN RANGE (THOUSAND FEET)	2	4	8	2	4	8	2	4	8
RELATIVE EFFECTIVENESS:									
AT 2000 FEET (610 m)	1.0	.71	.44	1.0	.74	.46	1.0	.90	.68
AT 4000 FEET (1219 m)	.37	.69	.44	.27	.61	.43	.63	.68	.58
AT 8000 FEET (2438 m)	.03	.21	.42	.02	.11	.29	.21	.35	.41

4. Optimum deployment height for all optimized designs is such that the flare burns out just before hitting the ground.

5. Increasing the size of the area of interest (in the 4000 ft (1219 m) fixed area mode) by up to a factor of 9 has little effect on optimized design.

6. In the search mode, increasing the fixation point density above 300 points/mile^2 (116 points/km^2) (corresponding to a fairly uncluttered terrain) has little effect on optimized design. Optimizing the flare system for lower fixation point densities requires greatly increased burning rates, but yields only small increases in effectiveness. Flare systems so designed have severely degraded effectiveness when used in higher fixation point density environments.

7. In the fixed target and fixed area modes, the best deployment point in a no-wind condition is downrange from the center of interest by an amount roughly equal to the deploy height. When wind conditions exist, the flare should be deployed at a position which carries it over the best no-wind deployment position after about 30% of the burn time is completed.

8. A hypothetical increase of 50% in composition "efficiency" (in the 2000 ft (610 m) fixed target mode) resulted in only an 11% increase in effectiveness.

While many of these results may apply to other flare system designs, we wish to emphasize that they are based <u>only</u> on our experience in applying the MODEL to the 155 mm flare.

CONCLUSIONS

The MODEL described constitutes the first total approach to optimizing the design of illuminating flare systems. Its assumptions are taken directly from experimental illumination requirements data. The MODEL optimizes design parameters (to a particular range and operational mode), and ultimate design decisions take user requirements (on range and mode) into account.

Application of this methodology to particular systems should enhance their performance. A design study for the 155 mm howitzer illuminating flare has been performed, and the results assessed. Use of the MODEL is clearly not limited to design of total systems, but will also be valuable for studying the practical implications of proposed engineering innovations (improved parachutes or compositions, reduced dead volume, etc.).

Refinements to the MODEL and its input assumptions and studies to assess their importance will involve the following: incorporation of terrain topology features, atmospheric effects, effectiveness of variable intensity flare pellets, and possible dwell time dependence on other factors (including illumination levels). In addition, studies are underway to test the sensitivity of results to all input parameters and to enlarge the experimental data base underlying the MODEL's input assumptions.

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